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A Geotechnical Facies Analysis of Some Quaternary Sediments Beneath Westernport Bay

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ABSTRACT: A combination of sedimentological and soils engineering procedures is used to reveal and assess the lateral and sequential variations in Quaternary strata underlying the main shipping channel of Westernport Bay.

Clays, which are abundant in the inner parts of the channel, exhibit a sequential stratigraphic memory relationship with the associated sands. In the outer reaches of the channel, where coarse gravels predominate, no sequential pattern is evident.

Field tests show that clays are generally of low plasticity with weak *in situ* shear characteristics and unconfined compressive strengths of $< 0{\cdot}3$ mPa. Sands are typically fine to medium grained with small uniformity indices and medium to high *in situ* densities. The coarse fluvio-littoral gravels are well graded and contain numerous pebbles and cobbles of basaltic rock.

Evidence supports the viewpoint that the pronounced lateral facies changes are expressions of variations in the energy of the depositional environment, coupled with a post-formational fall in relative sea levels. Data are limited and results preliminary.

Industrial and harbor construction works are now concentrated in areas where the finer grained Quaternary sediments are prevalent. Any future engineering activities, on the outer channel mounts, will tend to encounter the dissimilar and, in many ways, less amenable gravel facies.

INTRODUCTION

Westernport Bay is an excellent, relatively undeveloped deep water harbor on the south-eastern fringe of the Melbourne metropolitan area.

The Ports and Harbors Branch of the Public Works Department of Victoria has recently carried out a sea bed investigation of the Bay to aid determination of the feasibility of dredging and harbor construction works.

Detailed scientific investigations into the effects of present and future development of the area is well under way. A Westernport Bay Environmental Studies Group has been set up within the Victorian Ministry for Conservation, to report on environmental and developmental aspects. The PWD sea bed investigations, although specifically aimed at engineering feasibility considerations, provide additional data for incorporation in the comprehensive study.

Field and laboratory data which have been accumulated as a result of the sea bed investigation have added appreciably to the knowledge of soil conditions beneath the main shipping channel, and in the potential wharf sites. Four specific areas of detailed drilling are designated (1, 3, A, 4, Fig. 1). The areas extend along the main shipping channel from north of Long Island seaward to the mouth of the Bay. Drilling was by the barge mounted cable-tool method with adoption of surface powered rotary procedures for hard rocks and for specified bores in area 3.

The CSIRO Division of Applied Geomechanics was involved through the main contractors, Geomechanics, a branch of Decca Survey (Barton 1974).

GENERAL GEOLOGY

Westernport Bay occupies part of a Sunkland, or down-faulted area, between north-east/south-west trending block faults (Fig. 1). The Tyabb fault and its probable extension, the Clyde monocline, form the western boundary of the Sunkland against the up-faulted Mornington Peninsula. The eastern boundary is marked by the Heath Hill and Bass faults which uplift the Lower Cretaceous and Lower Tertiary rocks of the South Gippsland Hills. Numerous secondary faults cross the area, but for the sake of simplicity these are omitted from the sketch map (Fig. 1). The Westernport region is covered by 1:250,000 (No. SJ 55-9) and

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1:63360 (No. 868 Zone 7) Geological Survey of Victoria maps and by a CSIRO Division of Applied Geomechanics terrain evaluation report (Grant 1973). The general geology and stratigraphy has been outlined by Jenkin (1974) and Thompson (1974).

A considerable thickness of Tertiary and Quaternary sediments and Tertiary volcanic rocks in-fill the basinal structure of the sunklands. Mesozoic and Ordovician-Silurian sedimentary rocks are patchily exposed along the faulted margins and in the south coastal areas of French Island.

Practically all of the Bay is floored by Quaternary sediments. Seismic and drilling investigations indicate that in the main shipping channel, the Quaternary strata generally extends less than 50 ft (15 m) below sea bottom.

Present information appears to be inadequate for precise stratigraphic sub-division and correlation of the Quaternary materials. It is clear, however, that sea level was relatively lower than at present during deposition of the bulk of the sediments. The possibly lacustrine clays and sands of the northern inlet may be the equivalent of the Lower Pleistocene Heath Hill Silt (Thompson 1974). The deposits are not precisely dated and

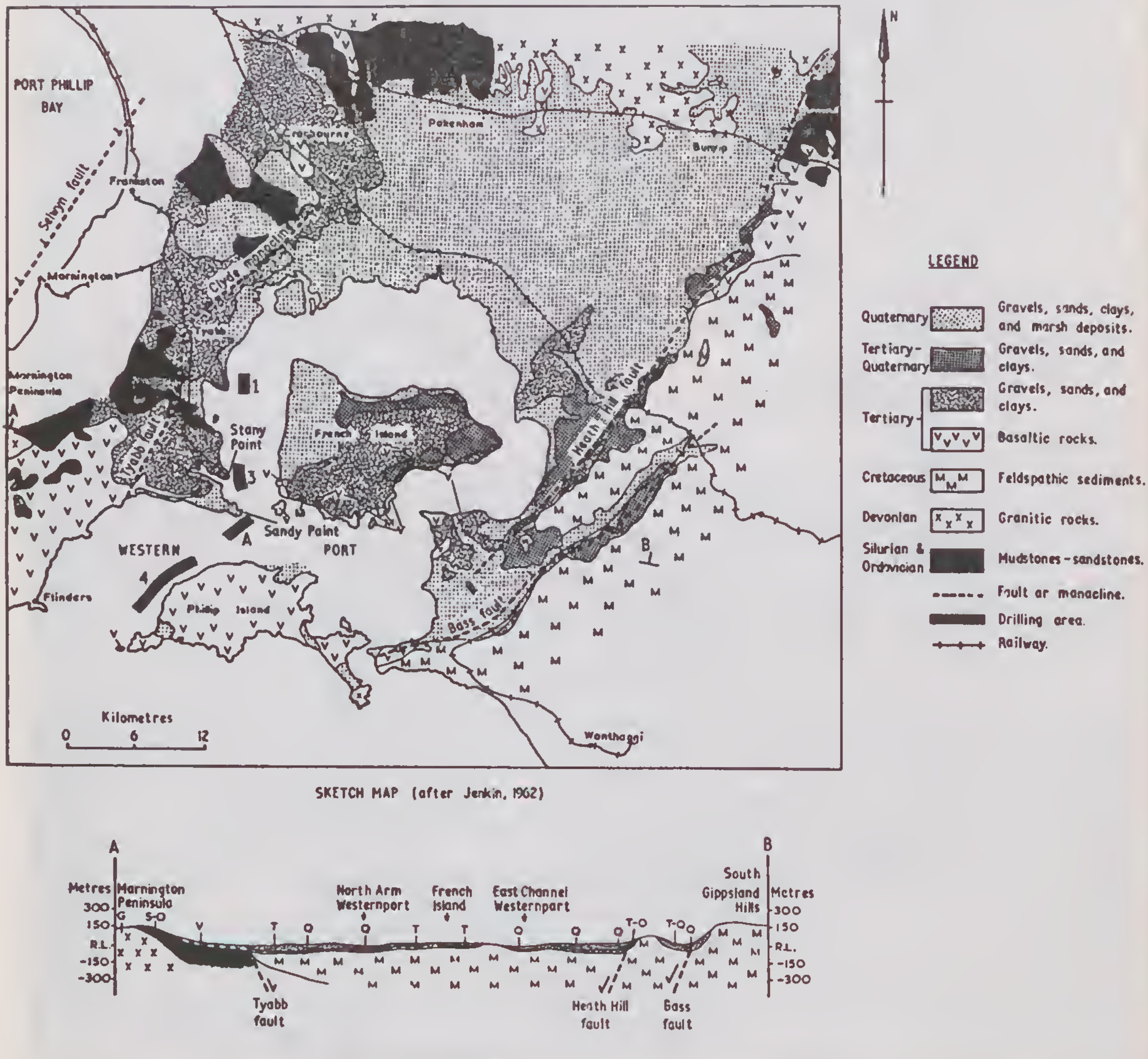


FIG. 1—Westernport geological map and cross-section.

an Upper Pleistocene age cannot be discounted. Evidence is presented in support of an age of 10-15,000 years for the Quaternary gravel beds of the outer channel.

CHARACTERISTICS OF THE QUATERNARY SEDIMENTS

An outline of the engineering classification and relative thicknesses of Quaternary soil types intersected during the drilling operation is presented in Table 1. The descriptive letter notation conforms to the Unified Classification System (Table II, from Means & Parcher 1964). In the inland parts of the channel the sediments are composed essentially of clays and sandy clays with subordinate sands. Towards the open sea, sandy coarse gravels and 'clean' sands are common. Sampling is biased in the outer area by the concentration of drilling on sea mounds within the confines of the channel.

Sands are generally poorly graded with uniformity coefficients of less than 5 and with log mean sizes within the fine to medium range. Eight size-distribution standard deviations, on a phi ($-\log_2$mm) scale (Folk 1968) ranged between 0·4 to 1·1. Further analysis of the particle-size curves indicate that the distributions are more coarse (negative) skewed towards the open sea. Only eight high quality undisturbed samples are available and further tests are needed to confirm the relationship. In this context it is interesting to note that a similar trend is evident in the recent superficial sub-bottom sands (M. Marsden, pers. communication). Environmental implications of the relationship are outlined in the discussion section. *In situ* densities, derived from 3 field tests, showed 18, 22 and 68 blows per 0·305 m, values which are indicative of a medium to very dense state.

Clays appear to be of illitic and kaolinitic types and are predominantly (57 per cent) soft in consistency. Clays adjacent to the sea bed are generally soft but, apart from this observation, no firm correlation is apparent between depth and consistency.

Three Geonar-vane tests of *in situ* soils, taken in shallow water 0·3 m below the sea bed in area 1, produced undisturbed test results of 8·5, 3·0 and > 100 kilopascals. It is of interest to note that adjacent on-shore drilling into probable Quaternary strata, in area 1 (Learmonth & Garratt 1969) encountered equivalent clays which gave indications of significantly higher *in situ* strength. Field observations taken during the sub-marine drilling showed that certain of the Quaternary clays rapidly increase in hardness after exposure to air. Investigations are proceeding to determine

TABLE I

ENGINEERING CHARACTER AND RELATIVE THICKNESS OF DRILLED SEDIMENTS.

AREA 1 and 3* (Total strata S3m.)		AREA A* (Total strata S3 m.)		AREA 4* (Total strata 81m.)	
UNIFIED CLASSIFICATION	PERCENT	UNIFIED CLASSIFICATION	PERCENT	UNIFIED CLASSIFICATION	PERCENT
CL	SS	CL	44	SW and GW-GM	27
CL-GC	21	SC-SM and SP	13	GW-GM	22
CL-CH	14	SW-GW	12	CL-GC	17
SW and SM	8	SP	7	SP	9
ML	1	ML	6	GW-GC	7
SC	1	SM	6	SW-GW	6
		SW-SC	4	SW and SM	4
		CL-GC	3	GW	4
		SC	3	GC-GM	2
		CL-SC	2	CL	1
				SW-SP	1

* Refer Figure 1 for localities, Table 2 for unified classification guide.

the reasons for the sub-aerial changes and to evaluate the variations in *in situ* consistencies.

THE FACIES ANALYSIS

An inspection of the tabulated uniformity indices for different localities along the length of the main channel (Table 1) provides evidence for the presence of distinct groups of different materials. In order to obtain a simple quantification of these lateral variations the proportions of clay-silt, as distinct from sand-gravel, are plotted at 3 specific points along the channel (Fig. 2). Three methods are adopted as the base for calculations:

1. Selection of all clay-silt index letters, from the Unified Classification table (Table 1) with subsequent summation of the thicknesses of the selected strata.
2. Summation of the thickness of the dominant fraction of each sediment unit.
3. Summation of the thickness of the coarsest fraction in each sediment unit.

The first method provides frequency data on all size components with equal weight allocated to minor constituents. The results are relevant to soil engineering investigations where, for example, the presence of relatively small fractions of clay can exert a significant effect on the behaviour of the material. The second alternative takes into account only the major size component of the soil and is insensitive to minor variations. The final alternative method is of greater relevance to sedimentary studies in that the maximum size of clast is largely dependent, at least in this instance (refer discussion section) upon the energy available in the depositional environment; a low velocity current, for example, cannot shift a large pebble. A record of the maximum size of clast is also pertinent to the 'dredgeability' of gravels in area 4.

All methods of calculation produce consistent results and show a reduction of clay-silt proportions in a seaward direction along the main shipping channel (Fig. 2). Implications of the lateral variations are considered in the discussion section.

In addition to the lateral changes outlined above, it is apparent that parallel variations in sediment sequence are also operative. Sequential changes are analysed by means of a simple mathematical technique (Selley 1970). The basic data is obtained by recording the number of times that one sediment type passes up or down into another dissimilar unit. Details are presented in a data array (Tables III A and IV A). In the top row of the data array shown in Table III A, for example, clay passed down into another type of clay 8 times, sand down to clay 4 times and silt and gravel down to clay 0 times. Diagonals in the data array table represent transference from one type of material into a different type of the same material. Recognition of such multi-storey lithologies is essential to the analysis, and use of the method in the absence of good exposures is therefore dependent on the availability of very detailed bore logs. An alternative procedure is available whereby the stratigraphic column is subdivided into fixed intervals and a record is made at each point. Results produced in this way are dependent upon the arbitrary length of the interval, since a small interval weights the data towards multi-storey transitions. While the fixed interval method is consequently objectionable for most sedimentological facies analyses it is sensitive to relative thicknesses of material types and possesses corresponding advantages in cases where this feature is important.

Data arrays showing the most common upward and downward transitions, in landward and seaward parts of the main channel (Tables III A and IV A) show that in both areas multi-storey transitions are most common. Facies relationship diagrams showing most common upward and downward transitions for these two areas are simply derived from the data arrays (Tables III, 1 and IV, 1). The diagrams confirm the preponderance of multi-storey lithologies, and show that in the seaward areas there is no 'memory' or order in the sequence between clay-silt, sand and gravel. The preponderance of clay-silt in the inland areas is again demonstrated.

The facies relationship diagrams which are discussed above, do not take into consideration the frequencies of transitions which would be anticipated under a random system. This bias is corrected in the following manner (Selley 1970). An additional predicted data array is produced by cross multiplying row and column totals and dividing the product by the grand total of the original array (Tables III B and IV B). The calculation method is based upon the assumption that the beds are arranged in a random sequence.

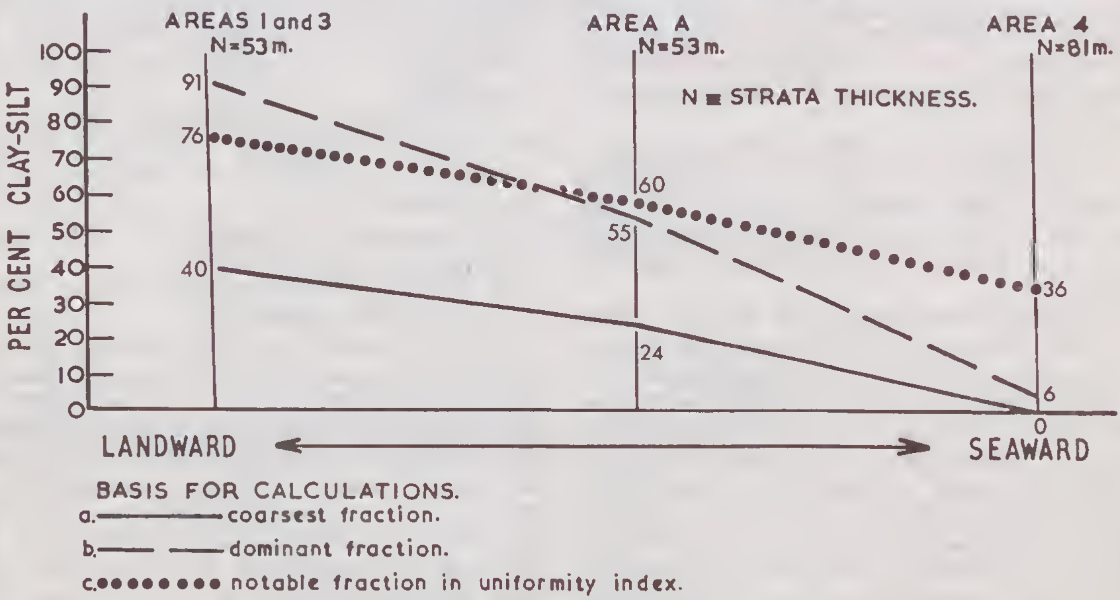


FIG. 2—Lateral facies change.

TABLE II

UNIFIED CLASSIFICATION, AFTER MEANS & PARCHER (1964).

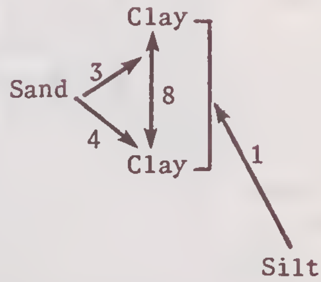
Field			Identification			Symbol	Typical Names
Coarse Grained Soils	Gravels More than 50 % larger than ¼ in	Clean Gravel	Wide range in grain size. Well graded.			GW	Well graded gravels, gravel-sand mixtures with few or no fines.
			Predominately one size. Poorly graded.			GP	Poorly graded gravels, gravel-sand mixtures with few or no fines.
		Gravel with fines	Containing non-plastic fines.			GM	Silty gravels, poorly graded gravel-sand-silt mixtures.
			Containing plastic fines.			GC	Clayey gravels, poorly graded gravel-sand-clay mixtures.
	Sands More than 50 % less than ¼ in	Clean Sand	Wide range in grain size. Well graded.			SW	Well graded sands, gravelly sands with few or no fines.
			Predominately one size. Poorly graded.			SP	Poorly graded sands, gravelly sands with few or no fines.
		Sand with fines	Containing non-plastic fines.			SM	Silty sands, poorly graded sand-silt mixtures.
			Containing plastic fines.			SC	Clayey sands, poorly graded sand-clay mixtures.
Fine Grained Soils			Dry Strength	Reaction to shaking	Toughness		
	Silts & Clays Liquid Limit less than 50 %		None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands.
			Medium to slight	None to slow	Medium	CL	Inorganic clays of low plasticity, gravelly clays, sandy clays, silty clays.
			Slight to medium	Slow	Slight	OL	Organic clays and organic silt-clay mixtures.
	Silts & Clays Liquid Limit greater than 50 %		Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous fine sandy or silty soils, elastic silts.
			High to very high	None	High	CH	Inorganic clays of high plasticity. Fat clays.
			Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity.
Highly organic soils			Identified by color, odor, spongy feel or fibrous texture			Pt	Peat or other highly organic soils.

Table III

Sequential Facies Relationship of 53 m of Quaternary Strata in Landward Parts of Westernport Shipping Channel (Areas 1 & 3).

	Clay	Sand	Silt	Gravel	
Clay	8	4	0	0	12
Sand	3	0	0	0	3
Silt	1	0	0	0	1
Gravel	0	0	0	0	0 Grand
	12	4	0	0	16 Total

A. Data array of facies limitations



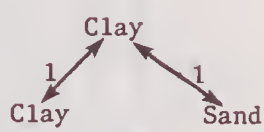
1. Facies relationship diagram showing the most common upward and downward transitions for each facies. (derived from A)

	Clay	Sand	Silt	Gravel	
Clay	9	4	0	0	13
Sand	2	1	0	0	3
Silt	1	0	0	0	1
Gravel	0	0	0	0	0 Grand
	12	5	0	0	17 Total

B. Predicted data array assuming a random arrangement of beds calculated by cross multiplying row and column totals and dividing by grand total.

	Clay	Sand	Silt	Gravel
Clay	+1	0	0	0
Sand	+1	0	0	0
Silt	0	0	0	0
Gravel	0	0	0	0

C. Matrix showing the difference between the observed number of transitions and those predicted assuming a random arrangement.



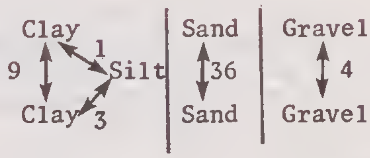
2. Corrected facies relationship diagram showing the upward and downward transitions which occur most often for each facies after allowing for the number expected had their arrangement been random (derived from C).

TABLE IV

SEQUENTIAL FACIES RELATIONSHIPS OF 135 m OF QUATERNARY STRATA IN SEAWARD PARTS OF WESTERNPORT SHIPPING CHANNEL (Areas 3 & 4).

	Clay	Sand	Silt	Gravel		
Clay	9	5	3	1	18	
Sand	8	36	0	1	45	
Silt	1	0	0	0	1	
Gravel	2	0	0	4	6	Grand
	20	41	3	6	70	Total

A. Data array of facies limitations



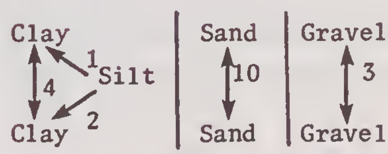
1. Facies relationship diagram showing the most common upward and downward transitions for each facie (derived from A)

	Clay	Sand	Silt	Gravel		
Clay	5	10	1	2	18	
Sand	12	26	2	4	44	
Silt	0	0	1	0	1	
Gravel	2	4	0	1	7	Grand
	19	41	3	7	70	Total

B. Predicted data array assuming a random arrangement of beds calculated by cross multiplying row and column totals and dividing by grand total.

	Clay	Sand	Silt	Gravel
Clay	+4	-5	+2	-1
Sand	-4	+10	-2	-3
Silt	+1	-1	0	0
Gravel	-4	0	+3	0

C. Matrix showing the difference between the observed number of transitions and those predicted assuming a random arrangement.



2. Corrected facies relationship diagram showing the upward and downward transitions which occur most often for each facies after allowing for the number expected had their arrangement been random (derived from C).

Each item in the observed data array is then subtracted from the equivalent item in the predicted data array to reveal a residual matrix (Tables III C and IV C). The matrix shows the most common upward and downward transitions which are expected after correction for a random arrangement of beds. The corrected data arrays, which have been produced from the residual matrices of Quaternary channel strata (Tables III, 2 and IV, 2) reveal a simple clay-silt sequence in the landward zones and a disconnected clay-silt, sand and gravel sequence beneath the more exposed waters of the outer channel. Implications of the findings are discussed below.

DISCUSSION

The quantification and description of the different facies has been outlined but little attempt has yet been made to explain either the mode of origin or the engineering significance of the variations.

Facies variations can arise as a consequence of difference in the source materials, in the transportation mechanisms and/or in the biogenic conditions. While biogenic effects may be of considerable secondary importance it is considered that, in these essentially detrital deposits, source type and transportation mechanisms are of overriding significance. The proximity to older Tertiary basaltic source rock in area 4 is relevant to the presence of abundant re-worked basaltic pebbles and cobbles within the Quaternary gravels. Basaltic pebbles also occur in the Quaternary strata as far inland as Sandy Point, and volcanic rocks, although much weathered, occur immediately beneath the Quaternary sediments on the inland channel areas adjacent to Stony Point. The proposition is therefore advanced that differences in the overall character of the sediments from inland and exposed channel zones are dependent more on the sorting effect of waves and currents than on differences in source material.

Despite great complexity in detail, an overall trend towards coarser sediments in the exposed parts of the Bay is evident not only in the Pleistocene strata but also in the Holocene deposits. A similar parallel trend is shown in the indicated increase in coarse skewness of sands in outer channel areas, possibly because of removal of the fine clay-silt component during current transport. In view of the above considerations and in the light of previous geological investigations (Jenkin 1962, 1974) it is clear that the inlet of Westernport Bay was in existence during the Quaternary. In the outer parts of the channels, in the Quaternary as at present, the water would be more exposed and the fringing coastal terrain would tend to be steeper. Transportation and deposition of gravel-sized clasts is feasible under these conditions. A sequential pattern of Quaternary deposition is evident only in sheltered waters of areas 1-3. In the outer channel, where a more changeable high energy depositional environment is anticipated, the sequential array is less ordered.

The minimum depth to the base of the gravel beds in area 4 is approximately 60 ft (18 m) below sea level. Since the beds are thought to be littoral or fluvio-littoral deposits (E. D. Gill, pers. communication), a post-depositional rise in sea level of some 70 ft (21 m) is indicated. In the likely absence of significant structural movements and on evidence of sea level changes from other areas (Gill 1973) an age of 10,000-15,000 years is proposed. This interpretation is complicated by the proximity of the site to the present outcrop of volcanic rocks on northern Phillip Island and the slight possibility that the deposits are submarine colluvial accumulations. No marine fossils have yet been recorded from the gravels.

The predominant soft-firm consistency of submarine clays, in areas 1-3, would appear to be advantageous for dredging and pile insertion, through the Quaternary strata, into the more competent underlying materials. It is of interest to note that, in area 3 near Stony Point, where extension of wharf facilities is possible, the underlying highly plastic Tertiary weathered basalt clays exhibit a remarkably even and apparently predictable, deep weathering profile.

The increase of sand and particularly coarse gravel on the sea floor beneath channel mounts in area 4 is very significant, as future removal of those obstructions is a distinct possibility. The procurement of truly representative samples of the gravel is extremely difficult and attendant estimation of 'dredgeability' would seem to be dependent upon future field trials. Sufficient data are available, however, to indicate the potential difficulties of dredging in this area. It is anticipated that if removal of the material is necessary, methods can be found to do this. Decisions on feasibility and design rest with the Ports and Harbors Branch of the PWD, Victoria.

CONCLUSIONS

Quaternary sediments are located at many points along the length of the main shipping channel of Westernport Bay. The analysis of the engineering logs prepared for the Westernport Sea Bed Investigation has shown that distinct differences are apparent between strata of the inland and seaward section of the channel. The tabulated unified classification indices give indications of these lateral lithological variations.

Three alternative calculation methods are used to demonstrate the consistent reduction in the relative proportions of clay-silt in a seaward direction. Sequential facies relationships, determined by application of a simple mathematical procedure, show that upward and downward transitions between different stratigraphic units fall into distinct groups. In the inner parts of the channel a simple inter-related clay-sand sequence is operative, while in the exposed areas apparently unrelated groups of clay-silt, sand and gravel are demonstrated.

Variability in the energy of Quaternary depositional environments is thought to be more significant in the creation of facies variability than differences in the availability of source materials.

A variety of constructional activities is likely in the inner harbor, where soil conditions are in general more conducive to development. Since the most obvious potential activity in the seaward extension of the main channel is in the removal of the relatively small channel mounds, the characteristics of the strata which are relevant to dredging operations are of over-riding importance. The presence of abundant well-graded coarse gravels, with many hard basalt pebbles and cobbles, is a significant factor of influence in the design of suitable methods of excavation.

The analytical methods outlined in this paper incorporate both soils engineering and sedimentology procedures. Such a blend of disciplines is of prospective value in the applied study and assessment of submarine and coastal sediments.

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